Paper 11 – World's largest Fiber Reinforced Polymer composite Mitre Gates for a new Lock in the Netherlands.

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ABSTRACT: This paper describes aspects of implementing large Fiber Reinforced Polymer composite Mitre Gates in a navigation lock in the Netherlands. The design approach is discussed, based on the functional requirements in conjunction with the hinges, the quoin blocks, gate paddles and the sealing requirements. Also the perceptual and general mental barriers for using FRP composites for this relatively large navigational structure are discussed. Specific requirements regarding the use of FRP composites are proposed to ensure structural safety and a durable performance for FRP composites in the wet infrastructure.

1 INTRODUCTION

Rijkswaterstaat the Netherlands is investing heavily in the wet infrastructure by increasing the navigational capacity of the main waterways, therewith reducing road traffic congestion and CO_2 emission.

One of these projects is the upgrading of the Wilhelmina Canal in Tilburg, the Netherlands to accommodate CEMT class IV ships. A new lock (named Lock III) will be built in 2015 replacing the two existing ones (Locks II and III).

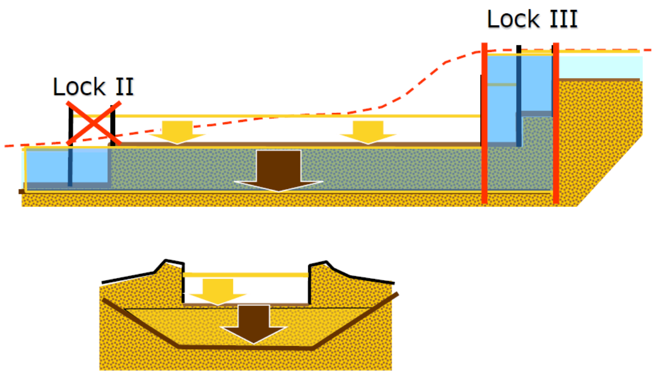

Figure 1: The new CEMT class IV Lock III in the Wilhelmina canal, The Netherlands.

The new Lock III will be equipped with the world largest FRP composite Mitre Gates in the world today. A single leaf of the upper Gates will have the dimensions of 6.2 x 4.8 m. The leaves of the bottom Gates will have the dimensions of 6.3 x 12.3 meters and are designed to resist a hydraulic head of 7.8 meters.

The main reasons for Rijkswaterstaat to choose FRP composites material in favor of traditional steel or wood, is the less intensive maintenance regime, which also results in low hindrance for water traffic during the 100 years of the intended design life. Also the use of tropical wood will be avoided, which contributes to one of the Rijkswaterstaat general environmental objectives.

2 EXISTING FRP COMPOSITE MITRE GATES

2.1 *'Spiering' Gates, Werkendam, The Netherlands*

These are small Gates made out of separate glass fiber reinforced polyester elements. The single corrugated skin plate is contained by two U-shaped profiles [1]. Chamber width: 6.0 m. Water depth: 3.3 m. Maximum hydraulic head: 2.5 m.

Figure 2: Spiering Mitre Gates, The Netherlands.

After 14 years of service in fresh water (similar circumstances as the new Lock III) no signs of delamination or osmoses of the FRP are observed.

Although 14 years of service is limited experience, it is an indication that FRP Composite is a suitable structural material to be used in the wet infrastructure.

The design was traditional and similar to that of a steel structure. The connections between the separate structural elements of FRP required efforts in the production and special attention during the design.

2.2 *Goleby Lock, France.*

These Gates originally designed as a full FRP Composite structure, are now supported by a metal frame to create additional stiffness in the structure. So from the structural point of view these Gates are not really a full FRP composite structure anymore.

Figure 3: Goleby Lock, France [1].
Chamber width: 5.1 m. Water depth: 2.2 m
Maximum hydraulic head: 6.0 m

These Gates have been out of service for some period. This however was not due to failure of the FRP Composite material itsef.

Figure 4: Goleby Lock, France. Supporting metal frames on the down stream side of the Gates.

2.3 *Spaarsluis Emmen, The Netherlands*

These Mitre Gates are relatively small. The dimensions of a single leaf are 5.0 x 3.6 m. Also the hydraulic head is quite low (less than 3 m).

Figure 5: Spaarsluis Emmen, in the Erica - Ter Apel canal, The Netherlands.

These Mitre Gates are the first full FRP composite structure made out of a one piece vacuum assisted polyester resin injection and glass fibers.

The years of good performance since 2012 again is an indication that if properly designed, FRP composites can be used successfully in the wet infrastructure.

3 TECHNICAL CONSIDERATIONS

Although long term experience was not available, Rijkswaterstaat decided to stimulate innovation and promote the use of FRP composites in the wet infrastructure. As standards and long term experience are limited today, additional requirements on long term behavior for this relatively new material have been formulated.

Considering the sizes of FRP Composite Mitre Gates built so far, the new Lock III is a big step forward in size and hydraulic head to be made out of FRP Composite.

The main reason for Rijkswaterstaat to accept FRP Composite Gates for this project was that the structure must be tolerant to cracks and damage should this, by any unexpected cause, occur during the 100 years of service life.

A production process of the FRP composite Gates by means of an integrated one-piece structural element could meet this requirement.

4 WORLDS LARGEST FRP COMPOSITE MITRE GATES

4.1 General construction

A singe lower head leaf for the new Lock III consists of a one piece FRP composite closed structure of 6.3 x 12.3 x 0.51 meters. No reinforcements by metal bars is applied.
Materials used are the commonly used combination of polyester and glass fiber.

Figure 6: One-piece FRP composite Mitre Gate leaves. Wilhelmina Canal, Tilburg The Netherlands.

The skin is solid 30 mm thick, with 5 mm solid webs spaced every 102 mm separated by Poly Urethane foam, connecting the front and back skin. The foam has no structural function.

An important design aspect is that the fibers connecting the skin and de webs are continuous, thus creating a high structural integrity and damage tolerance.

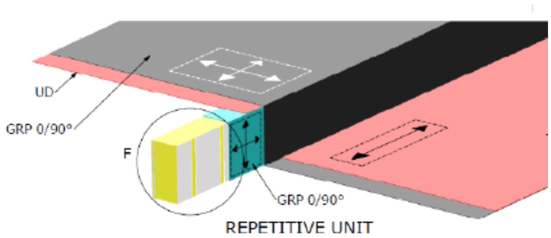

Figure 7: The Z-shaped continuous fiber and foam build-up used in the FRP Composite Mitre Gates.

For this project the flow holes of 1000 mm in diameter in the composite leaves created an extra challenge because of their position at high hydraulic loads. This was solved by adding horizontal structural beams made out of massive glass fiber polyester instead of foam at the locations with high stresses and strains.

These structural beams are also made out of the same FRP composite as the skin and the webs, but have a different fiber orientation to be effective for strength and stiffness mainly in the longitudinal direction of the beams.

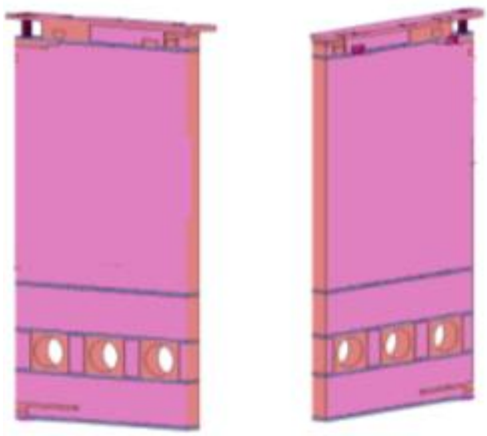

Figure 8: The structural beams (blue lines) on locations of high stresses and deflection.

The weight of one lower head leaf (excluding metal and wood appendages) is aproximately 22 tons.

4.2 Design criteria

4.2.1 Design codes

For this project the Dutch Design Recommendation CUR96:2003 [2] and revision 2014 were used to design the Gates. The CUR 96 guideline revision 2014 will be proposed to the European Committee for Standardization, as basis for a Euro Code Fiber reinforced polymers for load bearing structures.

An important issue is the long term behavior of the FRP Composite. Using the CUR96 rules for 100 years, the following material and conversion factors in the Serviceability Limit State are used:

γ_{m1} (material properties)	1.00
γ_{m2} (production)	1.20
γ_{ct} (temperature)	1.10
γ_{cv} (humidity)	1.30
γ_{ck} (creep)	1.24
γ_{cf} (fatigue)	1.10
Total factor (100 years)	2.34

At the Ultimate Limit State, a strain criteria of maximum 1.2 % is used.
In this case, as in many other structures made out of FRP composites, the maximum deflection is governing over the strength criteria.

4.2.2 Specific requirements Rijkswaterstaat

In order for this movable hinge Mitre Gates to function adequately, a correct load transfer to the quoin blocks during the hydraulic load is essential. Therefor the maximum permitted deflection perpendicular to the hydraulic load was set to 1/2000. The maximum deflection in the direction of the hydraulic load was set to 1/350.
The maximum deflection is to be met at the end of the 100 years of service.

Furthermore, the designer had to guarantee the correct working of the moving pintles and the gate paddles, assuming this deflection of the Mitre Gate leaves. Analysis were demanded to show that at maximum hydraulic loads on the leaves, the pintles do not carry any hydraulic loads, and the gate paddles are still able to move and operate correctly.

4.3 Material properties

All FRP components are made out of the same thermoset resin and fibers.
The resin used is a DCPD-polyester in accordance with Det Norske Veritas Grade 2, commonly used in ship building.

For the fibers a common E-Glass fiber is used with different fiber orientation for different positions:
(vf = 0,5).

Skin:	75% 0° + 25% 90°
Ex	32300 MPa
Ey	17850 MPa
Gxy = Gxz	6050 MPa

Structural beams:	80% 0° + 20% ±45°
Ex	33600 MPa
Ey	11200 MPa
Gxy = Gxz	6600 MPa

The choice of resin and fibers used in this project are based on experiences in ship building and fluid storage industry. Although other resins and fibers are avalable, an optimum in durability and costs has prevailed above a technically ideal solution.

4.4 *Deflection during service life*

Creep and relaxation is typical for FRP structures and also an important design aspect for Mitre Gates. No long term creep tests have been required, however, the deflection during service life is calculated. Special attention has been given to the assumptions to calculate the expected deflection after 100 years.
The theoretical deflection has been calculated by using all material and conversion factors and assuming no support of the sill. The full hydraulic load is assumed to be active on the Gates for 75% of the total lifetime on average, assuming normal lock operation.

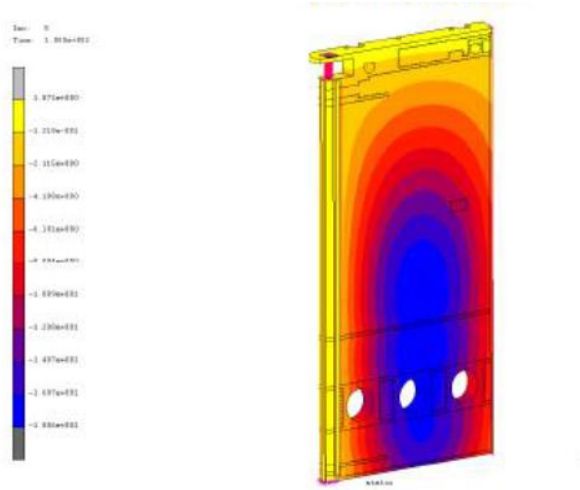

Figure 9: Calculated maximum deflection at SLS is 18 mm in the direction of the hydraulic load, at the vicinity of the structural beams.

Using these calculated results, the correct and reliable functioning over 100 years of the movable hinges, the heel posts and the gate paddles can be analyzed. The theoretical geometrical distortions are derived at several positions:

Hinges (bottom pintle)	4.0 mm
Gate paddles (center one)	1.4 mm
Heel post (quoin blocks)	1.3 DEG
Sill (leaf center)	14 mm

These theoretical geometrical displacements and rotations do not compromise a correct and reliable function of the Mitre Gates during 100 years of service. However for maintenance purposes, for example at the hinges and at the heel posts, these effects have to be considered.
In reality these deflections will be less because the sill generates an additional support and limits the

actual deflections occurring over time. The final design therefore is conservative.

First installation of the Mitre Gates is done ensuring no contact between the Gates and the sill. This will give a small leakage at the sill, but is acceptable in terms of water loss and dynamic effects. No rubber seals are used, thus making the main structure of the FRP Composite Gates maintenance free except for visual requirements.

Due to creep of the FRP the Gate leaves will make more and more contact with the sill over time, further decreasing the leakages of the Gates.

4.5 Strength

The strength is calculated in ULS with the maximum hydraulic load of 7.8 m.

Figure 10: Calculated maximum principle strain is 0.76% at ULS in the vicinity of the structural beams.

The criteria of maximum 1.2 % strain is met.
No ship collision loads have been calculated as a ship arrestor prevents this from occurring.

A typical side effect of making this type of one piece Mitre Gate leaf out of FRP composite instead of a traditional steel structure is the fully closed arrangement. Care should be taken to prevent floating obstacles like wooden logs to be crushed at the coin blocks during opening or closing of the leaf. Depending on the kind of obstacle, the FRP skin can be pierced, or the hinge can fail during opening or closing of the leave.
In either case, severe damage can be expected. Changes of this happening are considerably higher than in case of a traditional steel open structure, which most of the times gives the obstacle sufficient space not to be trapped at the heel posts.

4.6 Fatigue

Cyclic loads due to hydraulic pressure and Gate movements have been analyzed. The number of cyclic loads (N=500.000) in combination with the low cyclic stresses during normal operation, do not cause failure if analyzed according to the power law [3]. No detailed full scale fatigue tests have been performed.
Should there, by any unknown reason, be fatigue damage during operation, the degradation in stiffness of the structure in rate with the number of cyclic loads will give an early warning before sudden collapse can occur [4].

5 FACTORY PRODUCTION AND TESTING

The leaves are made by vacuum assisted resin injection on a one side stiffened mold, covered by a foil to create a vacuum of about 0.2 bar.
Fiber and foam are applied manually, following a fixed pattern.

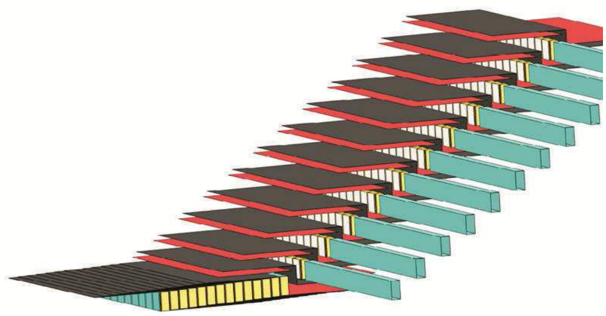

Figure 11: Pattern used to build up the foam and fibers onto the mold prior to resin injection (exploded view) [5].

During curing the temperature on the leaves is monitored. The amount of resin injected
is monitored, and the weight of the structure is checked after curing.

Figure 12: Mitre Gate leaf after curing and removing from the mold. All structural fiber elements have become a one-piece FRP composite structure.

Figure 13: Semi-finished upper Gate leaf, 6.2 x 4.8 m. Manufactured by FiberCore Europe, Rotterdam, The Netherlands.
Foil and runners still to be removed.

On test specimens, the following material properties are measured to check the achieved material strength and the quality of the curing process:

E-modulus ≥ 32.6 GPa,
UTS ≥ 549 MPa (ASTM 3039)
ILSS ≥ 20 MPa (ASTM 2344)
Tg ≥ 60°C (ASTM 7028)

As an additional Rijkswaterstaat demand, the stiffness of the Gates is checked at the factory before the Gates are accepted for installation. The overall stiffness is a good measure to check the soundness of the main structure.

The dynamic Eigen frequency is measured, and also the deflection under uniform applied load.
During these measurements the Gate leaves are supported on the front and heel posts only, like in real service conditions.

This simple check on structural soundness on every leaf produced, is an important aspect in making FRP structures in general acceptable for users and operators.

6 ULTRA VIOLET RESISTANCE

An iso-npg polyester topcoat is applied to prevent the influence of Ultra Violet radiation on the polyester resin. This also gives extra resistance against water.
The highest loaded parts of the structure are covered by water most of the time, so UV resistance is not a major issue.

7 MONITORING DURING OPERATION

For this project a continuous measuring system has been implemented in the FRP composite Mitre Gates.
This optical system measures the deflection during the Gate movements and during filling and emptying of the lock.
This way valuable information can be collected about the long term behavior of FRP composites for Mitre Gates for at least 10 years.

As this system acts like a monitoring system in service, it also gives on site proof of the structural integrity of the FRP structure. This is an important issue for both users and operators of this lock, taking away the negative perception and reluctance for "Plastic Gates".

8 REPAIR

Although damage by ship collision is prevented by ship arrestors, local damage could occur. Piercing the FRP skin is the most likely damage mechanism.
This kind of repair can be done on site, by adding enough fibers to restore the original amount of fibers in each direction according to the production drawings. Also the same resin as during production of the Gates must be used during repairs.

Repairs must be done in dry and clean conditions to ensure a good quality of the repair. Detailed procedures for repair will be part of the maintenance manual supplied by the building contractor.
This kind of repair is not as common as welding a traditional steel structure, but never the less acceptable from the structural safety point of view.

9 CREATING CONSENSUS

For the implementation of the largest FRP composite Mitre Gates in the world the following specific functional and performance requirements have been used by Rijkswaterstaat:

- Additional requirements on stiffness
- Continuous fiber arrangement and build up
- Damage tolerance in the structural design
- Design for 100 years of operation including effects of creep, humidity and fatigue
- Conservative design approach regarding the

theoretical forces on the leaves
- Additional testing on every final product
- Real time and continuous deflection monitoring during operation
- Reparability of local damage

These specific requirements ensure structural safety and durable performance, and also create consensus among designers, operators and users to accept the use of FRP composite as an innovative and reliable material.

10 CONCLUSIONS

The world largest FRP composite Mitre Gates will be implemented in a new lock in the Netherlands. Apart from design codes, specific requirements for the design approach and for ensuring structural safety and durable performance have been prescribed by Rijkswaterstaat.
These specific requirements also handles with the perceptual barriers of using the innovative FRP composite material for this relatively large structure in the wet infrastructure.

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